Int. Agrophysics, 2009, 23, 359-366

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Thermal properties of dairy cattle manure

M.A. Nayyeri, M.H. Kianmehr, A. Arabhosseini, and S.R. Hassan-Beygi*

Department of Agro Technology Engineering, Aboreyhan Campus, University of Tehran, P.O.Box 11365-4117, Tehran, Iran

Received February 14, 2009; accepted May 4, 2009

A b s t r a c t. The thermal properties of dairy cattle manure were measured at the different temperature and moisture content. The specific heat and thermal conductivity of dairy cattle manure increased linearly from 1.9925 to 3.606 kJ kg^{-1} °C^{-1} and from 0.0901 to 0.6814 W m^{-1} °C^{-1}, respectively. The moisture content was more effective than temperature in increasing the specific heat and thermal conductivity. The thermal diffusivity of dairy cattle manure varied from 1.13 to 2.94×10^{-7}m^2 s^{-1}. The effect of temperature was greater than that of moisture content in increasing the thermal diffusivity. Comparison between measured and estimated values, developed by regression models, showed that the accuracy of the equations for thermal properties are suitable for engineers to design thermal equipments of dairy cattle manure.

K e y w o r d s: dairy cattle manure, specific heat, thermal conductivity, thermal diffusivity

INTRODUCTION

Modern livestock activities may result in large emissions of ammonia, nitrous oxide, methane gas and odours from buildings and manure storage (Burton, 1997). These emissions lead to a large number of environmental problems (El-Ahraf and Willis, 1996). Waste management of manure has been widely recognized as a serious problem for livestock production (Ihara *et al*., 2006). When properly managed, manure can be used to provide nutrients to crops and to improve soil properties through accretion of soil organic matter. Drying is the common method to remove water from moist particle. Drying of manure is an effective approach to minimise pollution associated with it and use as fertilizer or soil amendment in pellet form. Dried manure has been used to prepare bed for dairy cattle, reducing the purchasing cost of bed material such as sand and wood chips and availability of dried manure at undesirable weather conditions. Historically the sun has been used for drying of manure. The main advantages of sun drying are low operating costs and less energy requirement. However, this process has several disadvantages, like pollution of the environment, long drying time and expletive approach of spread manure. These difficulties necessitate using new technology in dairy cattle manure drying process. Thus the physical and thermal properties of manure, such as heat and mass transfer, moisture diffusivity, thermal conductivity and specific heat are required for designing an ideal dryer.

Specific heat, thermal conductivity and thermal diffusivity are used in the engineering design calculations involving thermal processing of agricultural products. In agricultural materials, temperature and moisture content greatly influence the specific heat, thermal conductivity and thermal diffusivity due to the relatively high specific heat, thermal conductivity and thermal diffusivity of water. Different methods have been used by several researches to determine the specific heat of agricultural and food materials. The method of mixtures has been used as the most common technique for measuring the specific heat of agricultural products. In this method, the specific heat is determined for the solid by cooling the hot material in cold water and equating the heat losses by the substance to the heat gained by the cold water (Mohsenin, 1980; Tabil, 1999). The specific heat of spring wheat increased from 1.054 to 2.521 kJ kg^{-1} ºC^{-1} at temperature range of -33.5 to 21.8°C and moisture content of 1 to 23% dry base (d.b.) (Njie *et al.*, 1998). Yang *et al*. (2002) determined the specific heat of borage seeds in the moisture contents of 1.2 to 30.3 % (w.b.) and temperatures of 6, 10 and 20ºC. The specific heat of cumin seed increased with increase of temperature from -70 to 50°C and moisture content of 1.8 to 20.5% (d.b.) (Singh and Goswami, 2000). The specific heat of minor millet grains and flours increased from 1.33 to 2.40 kJ kg^{-1} ºC^{-1} with moisture content in the range of 10 to 30% (w.b.) (Subramanian and Viswanathan, 2003).

*Corresponding author's e-mail: ma_nayyeri@yahoo.com

The specific heat of four varieties of Iranian pistachio nuts as affected by moisture content and temperature was studied by Razavi and Taghizadeh (2007). The specific heat of berberis increased linearly from 1.9653 to 3.2811 kJ kg^{-1} ºC^{-1} at temperatures of 50, 60 and 70ºC and moisture contents of 19.3, 38.5, 55.4, and 74.3% (w.b.) (Aghbashlo *et al*., 2008).

Transient heat flow method using line heat source has been used by many researchers for determination of thermal conductivity of agricultural products. In this method, measurement of temperature at different time intervals helps to determine the thermal conductivity. The thermal conductivity of mushrooms was determined in the range of 0.2084 to 0.5309 W m^{-1} °C^{-1} (Shrivastava and Datta, 1999). The thermal conductivity of cumin seed increased with the increase of temperature from -50 to 50°C and moisture content from 1.8 to 20.5% (d.b.) (Singh and Goswami, 2000). The thermal conductivity of minor millet grains and flours increased from 0.026 to 0.223 W m^{-1} °C^{-1} with moisture content in the range of 10 to 30% (w.b.) and the thermal conductivity of flour was considerably less than that of grains (Subramanian and Viswanathan, 2003). The thermal conductivity of berberis increased linearly from 0.1324 to 0.4898 W m^{-1} °C^{-1} at temperatures of 50, 60 and 70ºC and moisture contents of 19.3, 38.5, 55.4, and 74.3% (w.b.) (Aghbashlo *et al.*, 2008).

The thermal diffusivity can be determined having specific heat, thermal conductivity and bulk density of a material (Eq. (1)):

$$\alpha = \frac{k}{\rho C_p}, \tag{1}$$

where: α is the thermal diffusivity, k is the thermal conductivity, ρ is the bulk density and C_p is the specific heat. Several researchers have already determined the thermal diffusivity from the measured values of specific heat, thermal conductivity and bulk density (Tansakul and Lumyong 2008; Singh and Goswami, 2000; Shepherd and Bhardwaj, 1986; Wratten *et al*., 1969; Yang *et al.*, 2002).

The aim of this study was to determine the specific heat, thermal conductivity and thermal diffusivity of dairy cattle manure as well as to develop mathematical models for prediction of the specific heat, thermal conductivity and thermal diffusivity of dairy cattle manure as a function of moisture content and temperature.

MATERIALS AND METHODS

Fresh dairy cattle manure was taken from an industrial cattleman (suburb of Tehran), homogenised completely and stored in a refrigerator at temperature of 5°C for experiments. Initial moisture content (*MC*) of fresh manure was determined using the oven method at 103°C for 24 h (ASAE, 2002). The experiments of *MC* were replicated three times to get an average value of *MC* for each sample. The initial moisture content of fresh dairy cattle manure was 82% (w.b.).

The moisture content and temperature were selected as the variables to simulate variations of thermal properties of dairy cattle manure affected by the actual process conditions during the dehydration. The experiments were preformed at temperatures of 40, 50, 60 and 70°C and moisture contents of 20, 40, 60, and 82% (w.b.). Each test was replicated three times and the average values are reported.

In this research, the mixtures method was used for measuring the specific heat of dairy cattle manure. The following assumptions could be considered for using this technique:
- heat loss was negligible during transfer of capsule from the hot air oven to the calorimeter,
- temperature of capsule and dairy cattle manure were equal at the end of heating,
- evaporation losses in the calorimeter were negligible during equilibration period,
- changes were not significant in the heat capacities of the calorimeter and the capsule within the range of studied temperature.

The experimental set-up was similar to the one used by previous researchers (Razavi and Taghizadeh, 2007; Singh and Goswami, 2000; Sreenarayanan and Chattopadhyay, 1986; Subramanian and Viswanathan, 2003). The apparatus consisted of a cylindrical aluminium capsule, with 15.2 mm diameter, 52.6 mm height and 2.1 mm wall thickness, to hold the samples. It was provided with a threaded lid to ensure no moisture was lost from the sample and no water entered into the capsule during the experiments, a T-type thermocouple with a temperature indicator, with 250 cm^3 capacity an insulated vacuum thermo-flask and a hot air oven.

The heat capacity of the calorimeter was determined experimentally. For this purpose a known quantity of distilled water at a known high temperature (maximum 70°C) was added to the calorimeter that contained a known quantity of distilled water at a known low temperature (room temperature). The system was assumed to be adiabatic. Therefore, the heat capacity of the calorimeter was determined by using of the heat equilibrium equation between the calorimeter, high and low temperature distilled water (Razavi and Taghizadeh, 2007; Shrivastava and Datta, 1999).

The heat capacity of cylindrical aluminium test capsule was also determined experimentally. For this purpose the capsule was added to the calorimeter containing a known quantity of distilled water at a low temperature (room temperature). The system was assumed to be adiabatic. The heat capacity of the capsule was given by using the heat equilibrium equation between the cylindrical aluminium, the calorimeter and distilled water in the calorimeter (Razavi and Taghizadeh, 2007; Shrivastava and Datta, 1999).

To determine the specific heat of dairy cattle manure, the capsule was filled with the dairy cattle manure and put into a hot air oven at desired temperature for at least one hour. Then the filled capsule was dropped into the calorimeter, containing a known quantity of distilled water at a known temperature, and then the equilibrium temperature was recorded. The specific heat of dairy cattle manure was calculated using the following heat balance equation (Razavi and Taghizadeh, 2007; Shrivastava and Datta, 1999):

$$C_p = \frac{\left(H_f + M_{cw}C_w\right)\left(T_e - T_{cw}\right) - H_c\left(T_m - T_e\right)}{M_m\left(T_m - T_e\right)} 4.1868, \tag{2}$$

where: C_p is specific heat of dairy cattle manure (kJ kg^{-1} °C^{-1}), M_m is mass of dairy cattle manure (kg), T_m is temperature of dairy cattle manure (°C), H_f is heat capacity of flask (kJ °C^{-1}), M_{cw} is mass of cold water (kg), C_w is specific heat of water (4.186 kJ kg-1 °C^{-1}), T_{cw} is temperature of cold water (°C), T_e is temperature of equilibrium (°C), and H_c is heat capacity of capsule (kJ °C^{-1}).

The transient-state heat transfer methods were used to measure the thermal conductivity of dairy cattle manure. The thermal conductivity was determined based on the relationship between the sample core temperature and heating time. A bare wire was used as a heating source. For an infinitely long line heater in an infinite, homogeneous, isotropic medium, the temperature rise at a radial distance *r* from the line heat source can be represented by the Eq. (3) (Mohsenin, 1980):

$$T - T_o = -\left(\frac{Q}{4\pi k}\right) Ei\left(-\frac{r^2}{4\alpha t}\right), \tag{3}$$

where: *Q* is the heat production of the line heat source (W) and can be calculated as $Q = RI^2$ in which *I* is the electrical current (*A*) and *R* is the electric resistance per unit length (Ω m^{-1}); k is the thermal conductivity (W m^{-1} °C^{-1}); *k* is the thermal diffusivity (m^2 s^{-1}); *t* is the time (s); and *Ei*(-*x*) is an exponential integral function. The Eq. (3) can be restated as:

$$T - T_o = -\left(\frac{Q}{4\pi k}\right)\left\{\ln\frac{r^2}{4\alpha t} - \gamma + \left(\frac{r^2}{4\alpha t}\right) - \frac{(1)^2}{2.2!}\left(\frac{r^2}{4\alpha t}\right)^2 \ldots \frac{(-1)^n}{n.n!}\left(\frac{r^2}{4\alpha t}\right)^n\right\} \tag{4}$$

where: γ is Euler's constant and equal to 0.58. For small values of $r^2/(4\alpha t)$, all terms after the second term at the right-hand side of the Eq. (4) would be negligible. Thus, the Eq. (4) can be expressed as:

$$T - To = \left(\frac{Q}{4\pi k}\right)\left\{\ln\left(\frac{r^2}{4\alpha e^{-\gamma}}\right) + \ln t\right\}, \tag{5}$$

The Eq. (5) means that the gradient of a plot of (ΔT) versus natural logarithm of time (*Ln* (*t*)) is equal to. The thermal conductivity can be calculated as:

$$k = \frac{Q\Delta Ln(t)}{4\pi\Delta T}, \tag{6}$$

$$k = \frac{RI^2}{4\pi S}. \tag{7}$$

The hot-wire thermal conductivity apparatus used in this study is shown in Fig. 1. The apparatus consisted of a brass cylindrical sample tube with 240 mm in height and 58.6 mm in inner diameter, a removable rubber top cover and fixed bottom base. A constant resistance heating wire with a diameter of 0.32 mm and length of 235 mm (11.49 Ω) was connected to a stabilised DC power source and the desired current was adjusted by resistor. A pre-calibrated T-type thermocouple with 0.8 mm diameter was installed for measuring the core temperature and glued approximately at the middle, about 1mm far from the heating wire. The assumption of an infinite medium required that the surface temperature of the sample holder was constant during the experiments. To validate this assumption, a second thermocouple was attached to the outer surface of the cylinder to monitor its temperature. A data logger multi-type thermometer (CHY502A, Taiwan) was used to collect the temperature data. The dairy cattle manure, filled in the sample container, was placed in an oven which was fixed at a pre-set initial temperature (40, 50, 60, and 70°C), for at least 2 h, in order to equilibrate to the desired initial temperature for the samples and the container. As soon as a stable temperature of the thermocouples was reached, a constant DC voltage was applied from the power supplier, resulting in a constant electric current through the heating wire. A digital multi-meter was used to monitor the electric current. Power levels of 2.5 to 6 W m^{-1} were used, which resulted in a temperature rise of the sample from 5 to 14°C at the thermocouple tip. The thermocouple temperatures were recorded by the data logger every

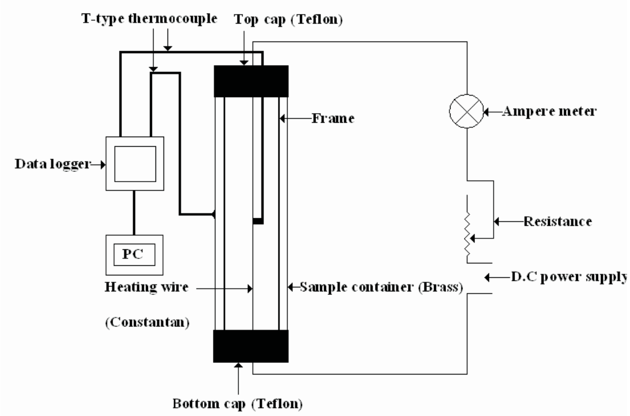

Fig. 1. Schematic of the apparatus used for measuring thermal conductivity of dairy cattle manure, PC – personal computer, DC – direct current.

second for 3 min. The recorded temperature values were then plotted against the natural logarithm of elapsed time. The slope (S) and the coefficient of determination (R^2) were determined successively for each experimental run using different data intervals. The slope for the highest R^2 was selected from the data intervals and used in the thermal conductivity determination (Casada and Walton, 1989; Murakami and Okos, 1988). Slopes with R^2 values of less than 0.990 were not used in the thermal conductivity determination. The thermal conductivity was calculated using the Eq. (7). The thermal conductivity was measured at temperatures of 40, 50, 60 and 70°C and moisture content of 20, 40, 60, and 82% (w.b.).

Thermal diffusivity of dairy cattle manure was calculated by using experimental data of thermal conductivity, specific heat and bulk density of dairy cattle manure by the Eq. (1). The average bulk density of dairy cattle manure in kg m^{-3} was obtained by dividing the sample weight recorded each time upon completion of sample loading by the effective volume of the sample capsule. The bulk density was measured in situ to eliminate the influence of loading pattern and container size on bulk density measurement.

RESULTS AND DISCUSSION

The variations in specific heat of dairy cattle manure with moisture content and temperature are presented in Fig. 2. The specific heat of dairy manure varied from a minimum of 1.9925 kJ kg^{-1} ºC^{-1} to a maximum of 3.606 kJ kg^{-1} ºC^{-1} for the experimental range of the variables. As depicted in Fig. 2, an increasing trend in the specific heat of dairy cattle manure was observed with the increase in both moisture content and temperature. Multiple regression analysis showed that there is a linear relationship between dependent variable of the specific heat (C_p) and the independent variables of moisture content (MC) and temperature (T) as follows:

$$C_p = 0.68298 + 0.025662T + 0.01306MC, \quad R^2=0.9925. \quad (8)$$

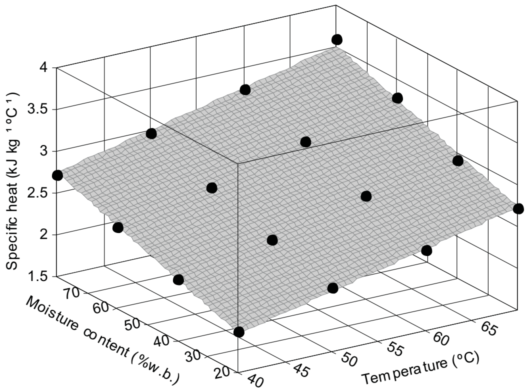

Fig. 2. Effect of temperature and moisture content on specific heat of dairy cattle manure.

The Eq. (8) was the first order linear model, so the response surface shown in Fig. 2 was also flat. Analysis of variance (ANOVA) table was constructed to evaluate the individual effect of independent variables on the specific heat (Table 1). The high F-value of regression confirmed the adequacy of the linear fitted model which accounted for 99.25% variation of the specific heat within the experimental range of the studied input variables (Gomez and Gomez, 1984). Comparison showed that the maximum differences between measured and estimated values of specific heat were within ±0.04 kJ kg^{-1} ºC^{-1}, which is desirable accuracy for estimating the specific heat (Fig. 3). Comparing F-values of the moisture content and temperature showed that the effect of moisture content on the specific heat was higher (high F-value) than the effect of temperature (low F-value).

The increasing trend of the specific heat of dairy cattle manure with increase in moisture content and temperature was in agreement with pervious findings of some researchers. The specific heat of borage seeds varied from 0.77 to 1.99 kJ kg^{-1} ºC^{-1} at temperatures in the range of 6 to 20°C and moisture content in the range of 1.2 to 30.3% (w.b.) (Yang *et al.*, 2002). Investigations of Tocci and Mascheroni (2008) revealed that the specific heat of kiwi fruit varied from 0.709 to 2.679 kJ kg^{-1} ºC^{-1}. The specific heat of cassava, yam and plantain was reported by Njie *et al.* (1998) as a function of moisture content and temperature. They found that there was similarity in specific heat of the three crops which increased with increasing of moisture content and temperature. Shrivastava and Datta (1999) found that the specific heat of mushrooms increased linearly from 1.7158 to 3.9498 kJ kg^{-1} ºC^{-1} with increase in temperature from 40 to 70°C and moisture content from and 10.24 to 89.68% (w.b.). Singh and Goswami (2000) investigations revealed that the specific heat of cumin seed was depended on both moisture and temperature and increased as a second-order polynomial from 1.330 to 3.090 kJ kg^{-1} ºC^{-1} with increasing of temperature and moisture content in the ranges of -70 to 50°C and 1.8 to 20.5% (d.b.), respectively, except for the 20.5% moisture content which displayed a linear relationship. The specific heat of whole and ground guna seed as a function of moisture content and temperature was determined by Aviara *et al.* (2008). They found that the specific heat of whole and ground seed increased from 1.391 to 3.020 and from 1.459 to 3.058kJ kg^{-1} K^{-1}, respectively, as the moisture content and temperature increased from 4.7 to 25.35% (d.b.) and 307.12 to 368 K. As well, Razavi and Taghizadeh (2007) research work showed that the specific heat of four varieties of Iranian pistachio nuts was a function of moisture content and temperature. They found that the specific heat increased from 0.419 to 2.930 kJ kg^{-1} ºC^{-1} with increasing of moisture content from 5 to 45% (w.b.). and temperature from 25 to 70°C as a non-linear polynomial. The specific heat of straw mushroom varied from 2.284 to 4.008 kJ kg^{-1} ºC^{-1} at temperature range of 50 to 80°C and moisture content range of 30 to 90% (w.b.) (Tansakul and Lumyong, 2008).

T a b l e 1. Analysis of variance (ANOVA) for effect of moisture content and temperature on specific heat, thermal conductivity and thermal diffusivity of dairy cattle manure

Source of variation	Sum of squares	Degree of freedom	Mean sum of squares	F_{cal}-value*	Probability
		Specific heat			
Regression	2.6772	2	1.3386	869.356	0.0000
MC	1.3645	1	1.3645	886.180	0.0000
T	1.3127	1	1.3127	852.528	0.0000
Residual	0.0200	13	0.0015		
Total	2.6972	15			
		Thermal conductivity			
Regression	0.5551	2	0.2775	817.493	0.0000
MC	0.5298	1	0.5298	1560.331	0.0000
T	0.0253	1	0.0253	74.656	0.0002
Residual	0.0044	13	0.0003		
Total	0.5595	15			
		Thermal diffusivity			
Regression	5.03×10^{-14}	3	2.51×10^{-14}	336.096	0.0000
MC^3	1.5120	1	1.5120	20.200	0.0000
T^2	4.8802	1	4.8802	651.991	0.0000
Residual	9.73×10^{-16}	12	7.48×10^{-17}		
Total	5.12×10^{-14}	15			

*Highly significant.

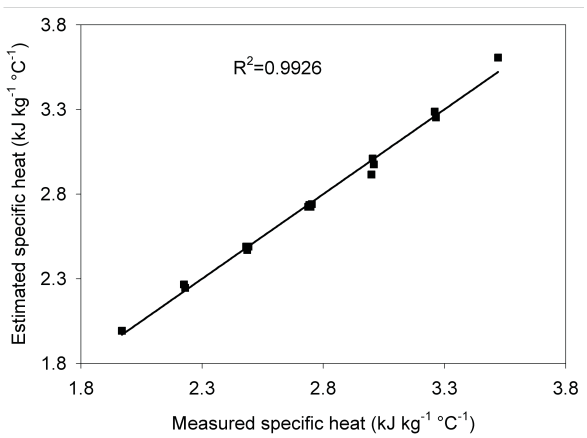

Fig. 3. Measured versus estimated specific heat values for dairy cattle manure.

The specific heat of berberis increased linearly from 1.9653 to 3.2811 kJ kg^{-1} ºC^{-1} at temperature range of 50 to 70ºC and moisture content range of 19.3 to 74.3% (w.b.) (Aghbashlo *et al.*, 2008).

The thermal conductivity of dairy cattle manure varied from 0.0901 to 0.6814 W m^{-1} °C^{-1} depending upon the moisture content and temperature within the experimental range of the variables. An increasing trend in the thermal conductivity of dairy cattle manure was also observed with the increase in both moisture content and temperature (Fig. 4). Multiple regression analysis showed that there is also a linear relationship between thermal conductivity (k) and moisture content (MC) and temperature (T) as follows:

$$k = -0.239615 + 0.00356\,T + 0.00813\,MC,\ R^2=0.9921. \quad (9)$$

The response surface presented in Fig. 4 was almost flat due to the fitted linear model. The analysis of variance (Table 1) indicates a greater effect of the moisture content (high F-value) than that of the temperature on the thermal conductivity. The magnitudes of respective regression coefficients in Eq. (9) also confirmed the results. The model seems adequately fitted based on the observation of high F-value as well as high coefficient of determination (R^2). The model accounted for 99.21% variation in the thermal conductivity within the experimental range of input variables (Gomez and Gomez, 1984). The maximum difference between measured and estimated values of the thermal conductivity was within ±0.02$\mathrm{Wm^{-1}\,°C^{-1}}$, which is desirable accuracy for estimating the thermal conductivity (Fig. 5).

Figure 4 revealed that the thermal conductivity of dairy cattle manure also increased with increase in moisture content and temperature, which is in general agreement with previous findings of some researchers. The thermal conductivity of wheat increased linearly from 0.107 to 0.128 W $\mathrm{m^{-1}}$ $\mathrm{K^{-1}}$ with increase in temperature from 2 to 20°C and moisture content of 13.12% (d.b.) (Bo iková, 2005). Investigations of Yang *et al*. (2002) showed that the thermal conductivity of borage seed varied from 0.11 to 0.28 W $\mathrm{m^{-1}}$ $\mathrm{K^{-1}}$ at temperature range of 6 to 20°C and moisture content in the range of 1.2 to 30.3% (w.b.). Martínez-Monzó *et al*. (2000) found that the thermal conductivity of apple due to vacuum impregnation varied from 0.57 to 0.67 W $\mathrm{m^{-1}}$ $\mathrm{K^{-1}}$ at temperature range 30 to 50°C. The thermal conductivity of straw mushroom varied from 0.212 to 0.668 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ at temperature in the range of 50 to 80°C and moisture content in the range of 30 to 90% (w.b.) (Tansakul and Lumyong, 2008). Shrivastava and Datta (1999) investigations showed that the thermal conductivity of mushrooms increased from 0.2084 to 0.5309 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ with increase of temperature and moisture content in the ranges of 40 to 70°C and 10.24 to 89.68% (w.b.), respectively. The thermal conductivity of cumin seed increased from 0.046 to 0.223 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ with increase in temperature from -50 to 50°C and moisture content from 1.8 to 20.5% (d.b.) and its variation with temperature and moisture content was represented by second order polynomial (Singh and Goswami, 2000). Aviara *et al.* (2008) found that the thermal conductivity of ground seed and kernel increased from 0.125 to 0.223 W $\mathrm{m^{-1}}$ $\mathrm{K^{-1}}$ and 0.107 to 0.191W $\mathrm{m^{-1}}$ $\mathrm{K^{-1}}$, respectively, as the moisture content and temperature increased from 5.6 to 19.13% (d.b.) and 308 to 368 K. Lisowa *et al*. (2002) investigation showed that the thermal conductivity of four apple varieties (Golden Delicious, Jonagold, Idared, and Jonathan) increased linearly at temperature in the range of 273 to 333K and moisture content of 50% (d.b.). Yang *et al*. (2003) investigations revealed that the thermal conductivity of rough rice increased from 0.080 to 0.138 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ at temperature range of 3 to 69°C and moisture content range of 9.2 to 17.0% (w.b.). A second order polynomial was developed to estimate the values of thermal conductivity as a function of moisture content and temperature by these researchers. Njie *et al.* (1998) investigations showed that the thermal conductivity of cassava, yam and plantain was a function of moisture content and temperature. Also, they found that the thermal conductivity of the three crops increased with moisture content and temperature. The thermal conductivity of brown rice increased linearly from 0.34 to 0.39 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ at temperature range of 10 to 50ºC and moisture content range of 14.9 to 30.1% (w.b.) (Muramatsu *et al*., 2008). The thermal conductivity of berberis increased linearly from 0.1324 to 0.4898 W $\mathrm{m^{-1}}$ $\mathrm{°C^{-1}}$ at temperature range of 50 to 70ºC and moisture content range of 19.3 to 74.3% (w.b.) (Aghbashlo *et al*., 2008).

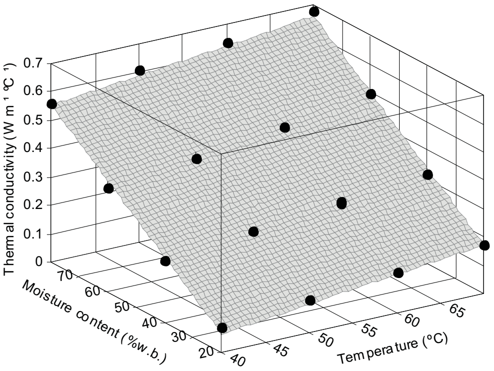

Fig. 4. Effect of temperature and moisture content on thermal conductivity of dairy cattle manure.

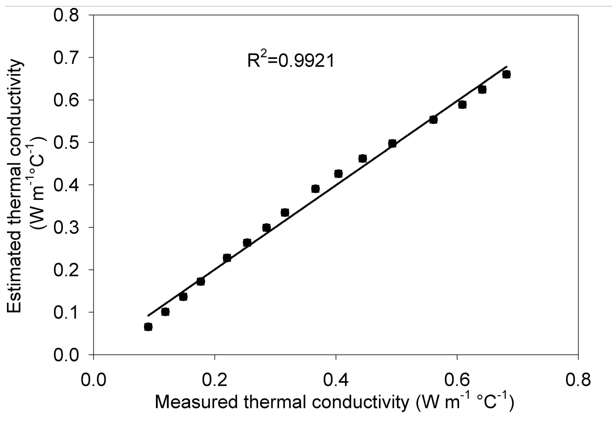

Fig. 5. Estimated thermal conductivity of dairy cattle manure versus measured values.

The bulk density values of dairy cattle manure were 351 to 1 220 kg $\mathrm{m^{-3}}$ at experimental moisture contents. The mean experimental value for thermal diffusivity of dairy cattle manure varied from 1.13×10^{-7} to $2.94\times10^{-7}\mathrm{m^2\,s^{-1}}$ at three replications in the moisture content range of 20 to 82% (w.b.) and the temperature range of 40 to 70 ºC. An increasing trend in the thermal diffusivity of dairy cattle manure was observed with increase of temperature. At increasing moisture content of dairy cattle manure from 20 to 82%, its thermal diffusivity increased first and then decreased beyond moisture content of 40% (Fig. 6). The reason was explained

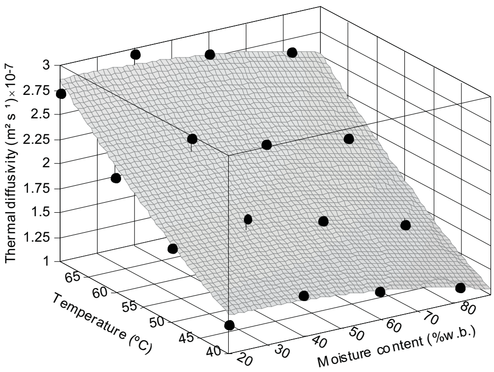

Fig. 6. Effect of temperature and moisture content on thermal diffusivity of dairy cattle manure.

to be the effect of dairy cattle manure bulk density at high moisture and also the total effect of thermal conductivity, specific heat and bulk density in the Eq. (1) with the change of moisture content (Mohsenin, 1980). This result for thermal diffusivity of dairy cattle manure was in general agreement with findings of some researchers. Kazarian and Hall (1965) found that the thermal diffusivity of wheat decreased consistently with moisture content and the thermal diffusivity of corn decreased first and then increased beyond 20% moisture content. The thermal diffusivity of wheat increased linearly from 2.40×10^{-7} to 2.68×10^{-7} m^2 s^{-1} with increase of temperature from 2 to 20 ºC and moisture content of 13.12 % (d.b.) (Bozikova, 2005). Investigations of Yang *et al.* (2002) showed that the thermal diffusivity of borage seeds varied from 2.32 to 3.18×10^{-7} m^2 s^{-1}. Lisowa *et al*. (2002) found that the thermal diffusivity of four apple varieties (Jonagold, Golden Delicious, Idared, and Jonathan) increased linearly from 1.229, 1.234, 1.257 and 1.346×10^{-7} m^2 s^{-1} with increase in temperature from 0 to 60 ºC and moisture content of 50% (d.b.). Tansakul and Lumyong (2008) calculated the thermal diffusivity from specific heat, thermal conductivity and bulk density for the straw mushroom in the moisture range of 30 to 90% (w.b.) and the temperature range of 50 to 80 ºC. The values ranged from 1.064 to 1.962×10^{-7} m^2 s^{-1}. Aviara *et al.* (2008) determined the thermal diffusivity of ground seed and kernel in the moisture and temperature ranges of 5.6 to 19.13% (d.b.) and 35 to 95 ºC as 3×10^{-7} to 8.468×10^{-8} m^2 s^{-1} and 1.768×10^{-7} to 4.214×10^{-8} m^2 s^{-1}, respectively. Singh and Goswami (2000) reported that thermal diffusivity of cumin seed decreased from 14.72×10^{-8} to 12.87×10^{-8} m^2 s^{-1} with increase in moisture content from 1.8 to 11.1% (d.b.) at 10°C, thereafter, it increased to 13.96×10^{-8} m^2 s^{-1} with increase of moisture content at 20.5% (d.b.). Iwabuchi *et al.* (1999) measured the thermal diffusivity of manure mixed with sawdust of 1.18×10^{-7} m^2 s^{-1}. Investigations of Loklari *et al.* (1957) showed that the thermal diffusivity of tobacco (Maryland) decreased from 7.61×10^{-8} to 1.18×10^{-7}m^2 s^{-1} with moisture content in the range of 2 to 20% (d.b.) and then increased from 7.92×10^{-8} to 7.61×10^{-8} m^2 s^{-1} with moisture content in the range of 20 to 35 % (d.b.). Wratten *et al.* (1969) calculated the thermal diffusivity from specific heat, thermal conductivity and bulk density for rough rice in the moisture range of 12 to 20% (d.b.) and the values ranged from 8.56×10^{-8} to 1.05×10^{-7}m^2 s^{-1}. The thermal diffusivity of Arabica and Robusta coffee parchments were calculated from the specific heat, thermal conductivity and bulk density as 2.36×10^{-7} to 1.69×10^{-7} m^2 s^{-1} and 2.08×10^{-7} to 1.44×10^{-7} m^2 s^{-1} (Chandrasekar and Viswanathan, 1999).

Multiple regression analysis showed a polynomial relationship between the thermal diffusivity (α) and the moisture content (*MC*) and temperature (*T*) as follows:

$$\alpha = 6.70\ 10^{-8} - 4.6\ 10^{-14}\ MC^3 + 4.476\ 10^{-11}\ T^2,$$

$$R^2 = 0.9812. \qquad (10)$$

The analysis of variance (Table 1) indicates a greater effect of temperature square (high F-value) than that of the moisture content on the thermal diffusivity. The magnitudes of respective regression coefficients in Eq. (10) also confirmed the results. The model accounted for 98% of variation in the thermal diffusivity within the experimental range of input variables.

CONCLUSIONS

1. The specific heat of dairy cattle manure increased with increase in both moisture content and temperature in the ranges of 20, 40, 60, and 82% (w.b.) and 40, 50, 60, and 70°C, respectively, from 1.9925 to 3.606 kJ kg^{-1} ºC^{-1}. The results showed that there is a strong linear correlation between the specific heat, moisture content and temperature.

2. The thermal conductivity of dairy cattle manure increased with increase in moisture content and temperature in experimental ranges. Its value lies between 0.0901 to 0.6814 W m^{-1} °C^{-1}. The relationship was found to be linear between thermal conductivity, moisture content and temperature.

3. The mean experimental value for thermal diffusivity of dairy cattle manure varied from 1.13×10^{-7} to 2.94×10^{-7} m^2 s^{-1}. An increasing trend in the thermal diffusivity of dairy cattle manure was observed with increase of temperature. By increasing moisture content of dairy cattle manure from 20 to 82%, its thermal diffusivity increased first and then decreased beyond moisture content of 40% (w.b.). The relationship existing between thermal diffusivity, moisture content and temperature was fit to a third order polynomial model.

REFERENCES

Aghbashlo M., Kianmehr M.H., and Hassan-Beygi S.R., 2008. Specific heat and thermal conductivity of berberis fruit (*Berberis vulgaris*). Am. J. Agric. Biol. Sci., 3(1), 330-336.

ASAE Standards, **2002**. S385.2. Moisture Measurement – Forages. St. Joseph, MI, USA.

Aviara N.A., Haque M.A., and Ogunjimi L.A.O., 2008. Thermal properties of guna seed. Int. Agrophysics, 22, 291-297.

Bo ikov M., 2005. Thermophysical parameters of chosen granular samples. Int. Agrophysics, 19, 203-207.

Burton C.H., 1997. Manure Management – Treatment Strategies for Sustainable Agriculture. Silsoe Inst. Press, Bedford, UK.

Casada M.E. and Walton L.R., 1989. Thermal conductivity of baled burley tobacco. Trans. ASAE, 32(2), 977-982.

Chandrasekar V. and Viswanathan R., 1999. Physical and thermal properties of coffee. J. Agric. Eng. Res., 73, 227-234.

El-Ahraf A. and Willis W.V., 1996. Management of Animal Waste: Environmental Health Problems and Technological Solutions. Praeger Press, Westport, USA.

Ihara I., Umetsu K., Kanamura K., and Watanabe T., 2006. Electrochemical oxidation of the effluent from anaerobic digestion of dairy manure. Bioresource Technol., 97, 1360-1364.

Iwabuchi K., Kimurab T., and Otten L., 1999. Effect of volumetric water content on thermal properties of dairy cattle feces mixed with sawdust. Bioresource Technol., 70, 293-297.

Gomez K. and Gomez A.A., 1984. Statistical Procedures for Agricultural Research. Wiley Press, New York, USA.

Kazarian E.A. and Hall C.W., 1965. The thermal properties of grain. Trans. ASAE, 8(1), 33-40.

Lisowa H., Wujec M., and Lis T., 2002. Influence of temperature and variety on the thermal properties of apples. Int. Agrophysics, 16, 43-52.

Loklari E.E., Galloway W.D., and Samfield M., 1957. The thermal conductivity of tobacco. Tobacco Sci., 28, 28-32.

Martínez-Monzó J., Barat J.M., González-Martínez C., Chiralt A., and Fito P. , 2000. Changes in thermal properties of apple due to vacuum impregnation. J. Food Eng., 43, 213-218.

Mohsenin N.N., 1980. Thermal Properties of Foods and Agricultural Materials. Gordon-Breach Press, New York, USA.

Murakami E.G. and Okos M.R., 1988. Measurement and prediction of thermal properties of foods. In: Food Properties and Computer-aided Engineering of Food Processing Systems (Eds P.R. Singh, A.G. Medina). Kluwer Academic Press, Boston, MA, USA.

Muramatsu Y., Tagawa A., Sakaguchi E., and Kasai T., 2008. Prediction of thermal conductivity of kernels and a packed bed of brown rice. J. Food Eng., 80, 241-248.

Njie D.N., Rumsey T.R., and Singh R.P., 1998. Thermal properties of cassava, yam and plantain. J. Food Eng., 37, 63-76.

Razavi S.M.A. and Taghizadeh M., 2007. The specific heat of pistachio nuts as affected by moisture content, temperature, and variety. J. Food Eng., 79, 158-167.

Shepherd H. and Bhardwaj R.K., 1986. Thermal properties of pigeon pea. Cereal Foods World, 31, 466-470.

Shrivastava M. and Datta A.K., 1999. Determination of specific heat and thermal conductivity of mushrooms (*Pleurotus forida*). J. Food Eng., 39, 255-260.

Singh K.K. and Goswami T.K., 2000. Thermal properties of cumin seed. J. Food Eng., 45, 181-187.

Sreenarayanan V.V. and Chattopadhyay P.K., 1986. Specific heat of rice bran. Agric. Wastes, 16, 217-224.

Subramanian S. and Viswanathan R., 2003. Thermal properties of minor millet grains and flours. Biosys. Eng., 84(3), 289-296.

Tabil L.G., 1999. Specific Heat of Agricultural and Food Materials. Res. Report, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Canada.

Tansakul A. and Lumyong R., 2008. Thermal properties of straw mushroom. J. Food Eng., 87, 91-98.

Tocci A.M. and Mascheroni R.H., 2008. Some thermal properties of fresh and osmotic ally dehydrated kiwifruit above and below the initial freezing temperature. J. Food Eng., 88, 20-27.

Wratten F.T., Poole W.D., Chesness J.L., Bal S., and Ramarao V., 1969. Physical and thermal properties of rough rice. Trans. ASAE, 12(6), 801-803.

Yang W., Siebenmorgen T.J., Thielen T.P.H., and Cnossen A.G., 2003. Effect of glass transition on thermal conductivity of rough rice. Biosys. Eng., 84(2), 193-200.

Yang W., Sokhansanj S., Tang J., and Winter P., 2002. Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. Biosys. Eng., 82(2), 169-176.